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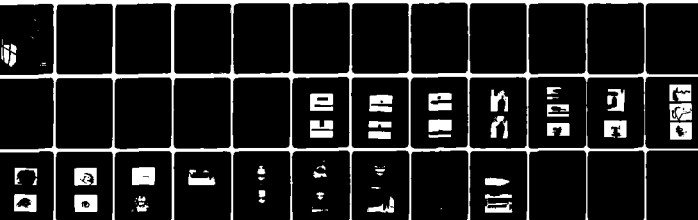
CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN IL F/G 11/4
INVESTIGATION OF THE MINIMUM DEPLOYMENT TIME OF A FOAM/FABRIC C--ETC(U)
SEP 80 A SMITH, B R CULBERTSON, R E MUNCY MIPR-FY-1456790021

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TECHNICAL REPORT M-281
September 1980

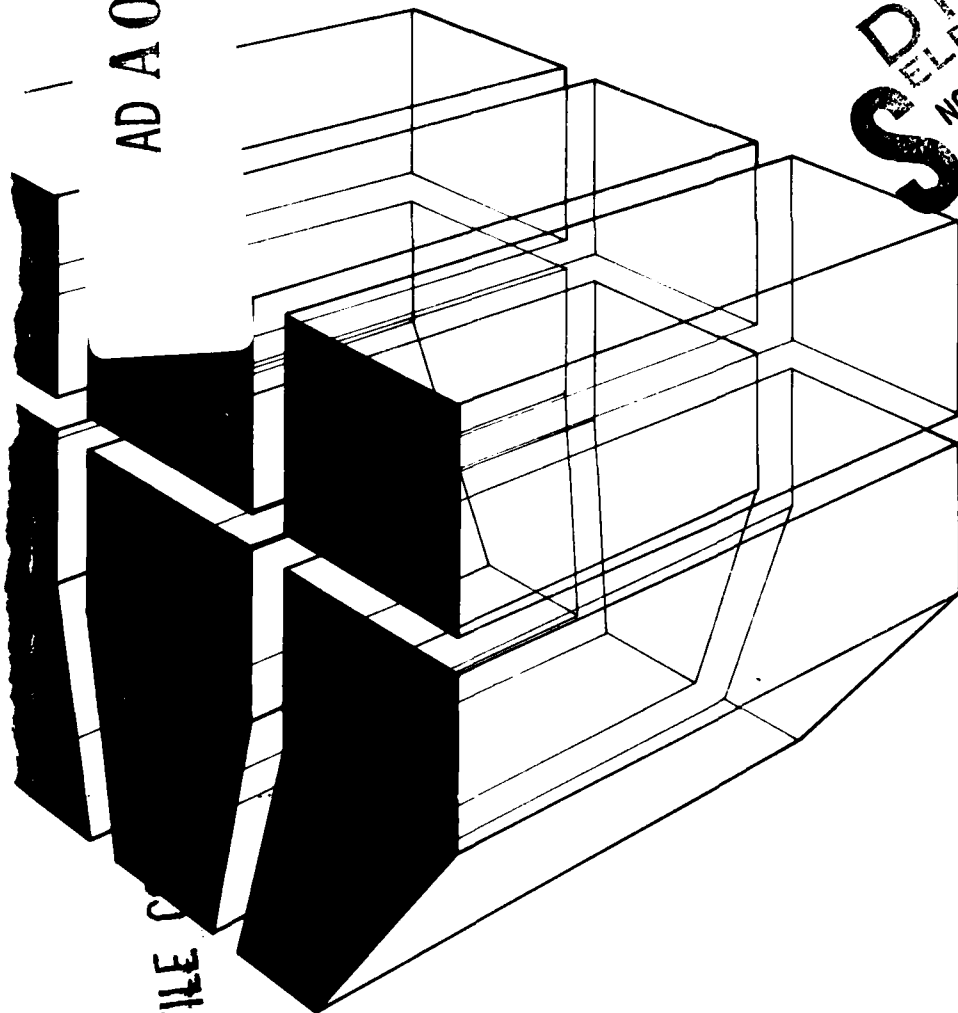
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INVESTIGATION OF THE MINIMUM DEPLOYMENT
TIME OF A FOAM/FABRIC COMPOSITE MATERIAL

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by
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14 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CERL-TR-M-281	2. GOVT ACCESSION NO. AD-A091658	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INVESTIGATION OF THE MINIMUM DEPLOYMENT TIME OF A FOAM/FABRIC COMPOSITE MATERIAL		5. TYPE OF REPORT & PERIOD COVERED FINAL rept.
6. AUTHOR(s) Smith B. R. Culbertson R. E. Muncy		7. PERFORMING ORG. REPORT NUMBER
8. CONTRACT OR GRANT NUMBER(s) MIPR -FY-145679021		9. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
10. CONTROLLING OFFICE NAME AND ADDRESS U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORY P.O. Box 4005, Champaign, IL 61820		11. REPORT DATE September 1980
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 1242		13. NUMBER OF PAGES 38
14. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
16. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
17. SUPPLEMENTARY NOTES Copies are obtainable from National Technical Information Service Springfield, VA 22151		
18. KEY WORDS (Continue on reverse side if necessary and identify by block number) foamed materials composite materials		
19. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the formulation, test design, materials, and evaluation of a very fast operating polystyrene foam-generating system. It was established that low-boiling-point solvents can be used to dissolve the polymer and act as the means of (1) providing gas pressure for discharging the material from a pressure vessel and (2) foaming the polymer within a cylindrical fabric sleeve. The discharge time was related to initial internal pressure. The minimum deployment time for a 0.5- X 10-ft (0.15- X 3.05-m) cylinder was found to be about 50 milliseconds.		

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FOREWORD

This research was conducted for the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Dayton, OH, as a part of their Laboratory Director's Basic Research Program. Funds were provided by Military Interdepartmental Purchase Request (MIPR) No. FY 1456790021. The Air Force Project Manager was Mr. S. R. Mehaffie; Mr. Malcolm Kelley and Mr. Harley Walker were also involved in the latter stages of the study.

The work was performed by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. Dr. R. Quattrone is Chief of EM. The fabric sewing was done in the Field Maintenance Shop of Chanute Air Force Base, Rantoul, IL; appreciation is expressed to Mr. Delmar Custer and his sewing personnel for their assistance.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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INVESTIGATION OF THE MINIMUM DEPLOYMENT TIME OF A FOAM/FABRIC COMPOSITE MATERIAL

1 INTRODUCTION

Background

Methods and materials developed during a 1979 study of a rapidly deployable foam system conducted by the Construction Engineering Research Laboratory (CERL) have essentially reduced the time required to produce a foam-filled fabric shape from about 1 minute to about 5 seconds -- an order of magnitude reduction in time.¹ A companion study has shown that foam-filled fabric cylinders are quite stiff, a result of fabric and foam characteristics and the composite action between them.²

The U.S. Air Force envisioned several potential applications for these foam/fabric shapes if the deployment time could be shortened by another two orders of magnitude, i.e., to 0.05 seconds for complete development of a 0.5- X 10-ft (0.15- X 3.05-m)-long cylinder. Therefore, they asked CERL to determine whether such a reduction in deployment time was possible and practical.

Objective

The objective of this study was to determine the minimum deployment time of a 0.5- X 10-ft (0.15- X 3.05-m)-long foam-filled fabric cylinder; the informal time goal for full deployment was 50 milliseconds.

Approach

This study was conducted in two steps:

1. CERL began preliminary evaluation and tests of (a) a two-component reactive system (mixed and injected into a fabric sleeve), (b) a single-component system of a fully polymerized material (dissolved in a solvent which would foam the mixture on demand),

¹A. Smith, *Investigation of Rapidly Deployable Plastic Foam Systems, Volume I: System Development*, Technical Report (TR) M-272/ADA076332 (U.S. Army Construction Engineering Research Laboratory [CERL], October 1979).

²A. Smith, S. S. Wang, and A. Y. Kuo, *Investigation of Rapidly Deployable Plastic Foam Systems, Volume II: Non-linear Deformation and Local Buckling of Kevlar Fabric/Polyurethane Foam Composites*, TR M-272/ADA076310 (CERL, October 1979).

and (c) a single-component foam generated and deployed into a fabric sleeve.

2. Based on these preliminary results, full-scale tests were made of a single-component system that generated foam from a polymer solution already contained within a fabric sleeve.

Scope

The study was limited to considering:

1. Commercially available materials
2. A fabric sleeve of high-strength cloth
3. A minimum foam density of 2 lb/cu ft (32 kg/m³).

The latter two requirements were self-imposed, based on CERL's previous experience with the stiffness of foam-filled fabric cylinders. The only physical properties measured were the density of the foam (in the preliminary phase of the study) and the deployment time (in the final phase of the study).

Safety

Signs were prominently displayed in the test area advising all personnel of potential hazard during preparation and conduct of all tests.

The chemical materials used in this study were all commercially available. Only the solvent presented a hazard to personnel; self-contained respirators with approved organic vapor filters were used in all open handling of the solvent. Protective clothing (including gloves) was also used by individuals to prevent skin contact and possible absorption of the solvent.

The testing consisted of a sudden discharge of material from a pressure container. Hearing protection was used by all operating and observing personnel during the tests. Eye protection (safety glasses or goggles) was also used.

A television/videotape recording monitor was in use during all phases of the test program in which the pressure container internal pressure was appreciably above ambient pressure.

The system described herein should be prepared and used only by experienced, trained personnel. The pressure containers should be adequately packaged and handled (during shipment) to prevent damage.

2 DEVELOPMENT

General

This study initially considered reactive two-component foam producing materials. (Polyurethanes, epoxies, phenolics, and polycarbodiimides were the candidate polymer systems.) However, it soon became apparent that the two-component systems required too much mixing time, even with high-velocity mixers. These systems also required an induction time (after mixing) before the rate of reaction became great enough to cause significant polymerization. Since either of these time factors would eliminate the possibility of deploying a foam/fabric shape within 50 milliseconds, and because CERL's earlier rapidly deployable foam study had shown that increasing the polymerization rate with additional catalysis could cause an uncontrollable runaway reaction, the single-component foam-producing system was selected for further study.

The earliest investigation into the feasibility of a single-component polystyrene foam-generating system was conducted by Monsanto Research Corporation for the U.S. Navy in 1966; this system was one of several considered as a promising alternative to conventional life raft inflation methods.³ Many other potential applications of this foam system were investigated by researchers at Monsanto, resulting in various formulation alternatives and system refinements.⁴

³I. O. Salyer, J. L. Schwendeman, and R. T. Jefferson, *Foam Optimization for Raft Development*, Contract No. N00178-68-C-0301/AD841131 (U.S. Naval Weapons Laboratory, September 1968).

⁴C. E. McClung, J. L. Schwendeman, I. O. Salyer, and A. L. Marcum, *Investigation of New Airdrop Energy Dissipator Material*, TR 75-98 AMEL/ADA021241 (U.S. Army Natick Laboratories, July 1975); I. O. Salyer, J. L. Schwendeman, A. Wojtowicz, R. T. Jefferson, and S. M. Sun, *Foam Flotation Systems for Personnel Wearing Body Armor*, TR 72-3-CE (C and PLSEL-87)/AD731000 (U.S. Army Natick Laboratories, July 1971); I. O. Salyer, J. L. Schwendeman, and R. T. Jefferson, *Foam Optimization for Raft Development*, Contract No. N00178-68-C-0301/AD841131 (U.S. Naval Weapons Laboratory, September 1968); J. L. Schwendeman, S. M. Sun, and I. O. Salyer, *Instant Foam System Development*, Report MRC-DA-559, Sandia Laboratories, Contract No. SLA 82-8805 (Monsanto Research Corporation, May 1976); and S. M. Sun, J. L. Schwendeman, and I. O. Salyer, *Feasibility of Use of Plastic Foams for Small Vessel Flotation Devices*, U.S. Coast Guard Report CG-D-21-76/ADA021076 (U.S. Coast Guard, January 1976).

Monsanto's single-component foam system had five constituents:

1. Resin — polystyrene resin was generally used, although other resins were evaluated. High molecular weight resin performed best because its solubility characteristics changed drastically as the foam expanded from the solution. High molecular weight resin was found to be less affected by the vapor phase of the solvent.

2. Pneumatogen/solvent — low molecular weight, low-boiling-point solvents worked best. Dimethyl ether and methyl chloride were most frequently used; methyl chloride was preferred because of its lower flammability. At low temperatures or under pressure, the pneumatogens dissolved the resin and formed viscous, syrupy solutions. When pressure was released above the boiling point of the pneumatogen, the vapor pressure of the solvent caused a phase change to a gas. Since the resin was practically insoluble in gas, it trapped the gas in its syrupy mass, causing expansion. Foam-generation rate and density generally followed the vapor pressure of the pneumatogen/solvent. Figure 1 shows the vapor pressure curves of methyl chloride; Figure 2 shows the vapor pressure of the atmosphere over the polymer solution. Figures 1 and 2 indicate that the internal pressure of a closed vessel containing a polystyrene solution is a function of temperature and is typically lower than over pure solvent alone.

3. Auxiliary solvent/blowing agents — additional solvents such as tetrachloroethylene and halogenated hydrocarbons (refrigerants) acted as solvents and helped reduce foam system viscosity. Freon 11, Freon 12, and Freon 13B1* were all used successfully in instant foam formulations. However, they assisted in the foaming process only if the ambient temperature was above their boiling point. Otherwise, their solution effects were prevalent, and they resulted in foams that remained soft for a period of time after formation.

4. Nucleating agent — small, solvent-insoluble granular powders were used to encourage gas bubble formation. The nucleating agents helped generate finer celled foams. Silica flour, glass microballoons, zinc stearate, and other materials were used for this purpose; the glass microballoons performed best.

5. Internal lubricants — viscosity modifiers such as silicone oils, soaps, and related materials eased the flow

*DuPont registered trade names.

of the solution through orifices by reducing internal and external friction, and allowed better foam expansion. The lubricants also served as surfactants which helped trap gas as bubbles, resulting in closed-cell foams; surfactant action is essentially analogous to soap solution bubble formation.

The formulation selected for investigation during this study (Table 1) is based on the materials and proportions which proved most successful during the Monsanto studies.

Formulation

Proper mixing and blending of the ingredients listed in Table 1 yielded foams (at room temperature) that were about 1.8 lb/cu ft (2.9 kg/m³) and had 70 percent or greater closed-cell content. Foam density varied with ambient temperature, since the expansion of the pneumatogen generally followed Charles' Law (volume-temperature relationship):

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad [\text{Eq 1}]$$

Pressure System Container

The single-component foam mixture had to be maintained in a pressure system to prevent the solvent from escaping and foaming the polymer. The selected diameter for the preliminary pressure system container was 2.5 in. (63.5 mm) and the length was 5 in. (127 mm).

The container had to be capable of withstanding internal pressure caused by the highest vapor pressure of the lowest boiling solvent in the system at the maximum storage/function temperature. In the formulation selected, the maximum pressure was about 250 psig (1.7 MPa) at a temperature of 160°F (71°C). The pressure vessels initially considered were carbon dioxide cartridges similar to those used for inflating life vests; however, because of their designed high pressure rating, these containers proved too heavy. Consequently, the investigation concentrated on adapting commercially available aerosol cans for use as containers. Seamless, two-part cans (can body and closure cap) offered the highest pressure capability, i.e., an internal pressure greater than 270 psig (1.86 MPa). The closest available standard diameter to the selected 2.5 in. (63.5 mm) was 2.08 in. (52.83 mm); the nearest standard length was 4.68 in. (119 mm).

The selected container was an impact-formed (deep-drawn) aluminum can made by the Peerless Tube Co.

The can opening was 1 in. (25.4 mm) in diameter (Figure 3), with a rolled edge designed for a crimp-in closure cap (Figure 4). The closure cap, made by the Precision Valve Company, is shown in Figure 5; it is installed in the can by placing it into the opening. A collet is then inserted which expands a ring of the cup within the neck of the can beneath the edge rolled by the crimping machine. An epoxy cement (coated in the cup by the manufacturer) seals the can. The expanded metal prevents the cup from popping out.

The cup had a 0.150-in. (3.81-mm) opening designed to accommodate an aerosol valve. This opening was too small to allow the expulsion of the viscous foam mixture and had to be enlarged to 0.375 in. (9.5 mm).

Valve Release Mechanism

The pressure system was sealed by altering the opening in the closure cup and cementing in a straight-through orifice device (Figure 6). This device used a spring-loaded plunger in contact with a rubber O-ring to effect the seal (Figures 7, 8, and 9). A cap was used to compress the spring in the outlet port. This cap was pinned to the outlet orifice with a spring clip (Figure 10).

The strength of the compression spring required to maintain the seal was calculated based on the maximum internal pressure anticipated for the system and the throat area of the orifice. Pressure tests were conducted to verify the seal, using a device which allowed pressurization by compressed nitrogen while the seal was submerged in water. Figure 11 shows the test fixture.

Pressure Testing

The entire can/cup/seal assembly was pressure-tested after the integrity of the O-ring was verified at operational pressure (Figure 12 shows the test fixture). These tests showed that the cup had to be crimped in the can twice; the crimper's expansion collets were segmented, and crimping a second time -- after slightly rotating the can -- gave a much stronger, continuous crimp. The can/cup/seal tests demonstrated that the assembly was strong enough to contain the foam system up to the maximum design pressure.

Release Mechanism Function

Considerable effort was spent developing a reliable foam release mechanism. Although the spring clip did an adequate job of maintaining the seal, it had to be manually removed to effect foam release.

3 PRELIMINARY TEST AND EVALUATION

Specimen Preparation

Test specimens were prepared using the pressure container system described in Chapter 2. The foam formulation and quantities are listed in Table 2.

The "A" ingredients listed in Table 2 were placed in the container; the container was then tumbled to mix the ingredients. Next, the can and contents were chilled in dry ice until the equilibrium temperature was reached. The "B" ingredients were then placed in the container.

It was observed that if the "A" and "B" solvents were placed in the container on top of the resin (which nearly filled the container to capacity), they would become trapped by air in the void volume of the resin and would not flow down into the plastic granules; they could also "seal" the container top by immediately dissolving some of the resin. This problem was solved by inserting a glass funnel stem into the resin, then pouring the solvents into the funnel. This placed the solvents at the bottom of the container and prevented them from becoming trapped and/or "sealing" the container top.

The container cups were quickly crimped into the cans while the cans were still below the boiling point of the methyl chloride (i.e., lower than -25°F [-32°C]). The plunger, spring, and cap were then installed and held in place by the spring clip. (Gloves were used throughout the loading operation to avoid frostbite and to reduce the possibility of warming the container and contents until the unit was completely loaded and sealed.)

After the foam system was loaded, the units were removed from the cold environment, allowed to warm to room temperature, and tested for leaks by submerging them in a warm water bath (about 100°F [33°C]).

The units were then placed in an end-over-end mixer to blend/dissolve the foam materials (Figures 13, 14, and 15). The mixer was operated by a timer which maintained a cycle consisting of 15 minutes on, alternated with 2 hours off. After a minimum of 24 hours of tumble mixing, the foam units were placed in an oven and kept at 120°F (49°C) for a minimum of 24 hours. During the heating period, the units were up-

ended at least four times to assist in the mixing (dispersion) of the insoluble glass microballoons.

Finally, the units were conditioned to the operating test temperatures and tested.

Tests and Results

One of each of the conditioned test specimens was tested in a water bath at -65 , -10 , 27.5 , 67 , 107 , and 160°F (-54 , -23 , -2.5 , 19 , 42 , and 71°C). The release mechanisms were activated manually by removing the spring clip retainers while the can was held on the surface of the water (the cans were very near neutral buoyancy and sank slowly). Figure 16 shows typical extruded foam. The initial expulsion of material was very rapid. The rate decreased as the pressure dropped and a noticeable cooling of the container occurred. (The temperature dropped as the expanding solvent absorbed heat from the system.) The container did not empty completely during any of these tests, but it did fill with foam. Figure 17 shows a cutaway view of a can and its foam contents after foam generation. In general, the higher the temperature (pressure), the greater the volume amount of material expelled from the container. The higher temperature also caused faster foam generation. At the higher temperatures, the viscosity of the solvated resin was lower, thus easing the flow through the orifice. The solution became more and more viscous as the temperature dropped, until it became too viscous for the reduced gas pressure to force it through the orifice (Figure 18).

Initial tests were conducted with orifices 0.15 in. (3.81 mm) in diameter. The foam formed was about 1 in. (25.4 mm) in diameter (Figure 19). When the orifice diameter was increased to 0.22 in. (5.59 mm), the diameter of the foam increased to about 1.75 in. (44.4 mm). The final design orifice was 0.375 in. (9.52 mm) — the diameter of the foam produced was 2.5 in. (63.5 mm).

The throat length of the outlet device also had a significant influence on the diameter of the foam; long throats act as forming dies and restrict diametrical expansion while increasing the velocity of axial foaming.

Other Tests

The amount of resin that can be held in solution at -65 and 160°F (-54 and 71°C) was evaluated. It was found that up to about 80 percent (by weight) of resin can be adequately held in solution at these two temperature extremes. High resin content increases viscosity and the lowest foam-forming temperature increases correspondingly.

The maximum resin content for the broad temperature range used in this study was about 60 to 75 percent. Even at this concentration, the viscosity became so high at -10°F (-23°C) that material flow ceased and no foam was produced. Those units conditioned to -10 and -65°F (-23 and -54°C) demonstrated these results. Of course, at -65°F (-54°C) the methyl chloride did not boil; heat gain from the water bath at 27.5°F (-2.5°C) was too slow to warm the units enough to get the desired performance.

Evaluation

The units tested at the various temperature conditions gave the density and dimension results shown in Table 3 and Figures 20 through 22.

Foam units were also evaluated (at room temperature) by ejecting foamable material into cloth and/or polyethylene tubular sleeves. The lightweight nylon cloth sleeve was made so it would create a donut shape when filled. However, the restriction of the cloth prevented the foam from fully expanding, and the sleeve did not fill completely. (Figures 23 and 24 show the results of one test.) The foam did not bond to the fabric during any of the tests.

The straight tube of polyethylene film performed somewhat better, although it did not fill completely with foam. The gas produced by the unit rapidly inflated the sealed tube and the foam filled the tube from end to end, i.e., 48 in. (1.2 m). A tube 3.5 in. (88.9 mm) in diameter did not fill completely (Figure 25). Gas pressure in the bag was higher than atmospheric pressure, thus restricting foam expansion. The foam density in this test was 3.5 lb/cu ft (56 kg/m³).

These preliminary tests demonstrated that making the single-component foam was feasible, but that generating the foam and concurrently or subsequently injecting it into a sleeve was not a good method of producing a long, foam-filled cylinder. Thus, making the foam from a solution contained within the sleeves was determined to be the best approach. This approach would work if the entire sleeve assembly were contained within a pressure vessel before functioning.

4 FULL-SCALE TEST AND EVALUATION

Design of the Pressure Vessel

There were three conditions that the fabric bag/solution pressure vessel had to meet:

1. The cylinder had to be capable of withstanding the maximum internal pressure with a reasonably high safety factor; this would allow the vessel to be reused without concern for fatigue.

2. The vessel had to be made of materials that would eliminate any likelihood of corrosion during the test program.

3. The vessel had to be sized so it could hold the fabric form (with contents) in such a way that, when released, the foam-filled form would expand axially along the length of the cylinder.

The first and second design conditions were met by using schedule 40 stainless steel pipe and end plates sized in accordance with American Society of Mechanical Engineers rules for pressure vessel construction.⁵ The pipe used was 6 × 12 in. (0.15 × 0.30 mm) and was made of Type 304 stainless steel. The initial design included a 1/2-in. (13-mm) plate welded on one end (this plate had a threaded hole through the center, a small pipe nipple, and valve for pressurizing gas control) and a closure device consisting of a bevelled flange welded on the open end with a mating bevelled lid of 1/2-in. (13-mm) stainless steel plate fitted with O-rings to effect the seal. A split ring with machined internal bevels secured the lid to the flange by an inclined plane or wedge clamping action when the ring was brought into contact with the flange and the lid lip.

After the pressure vessel was assembled, it was tested to an internal pressure of 300 psi (2 MPa). However, because the vessel's heavy lid could become a dangerous projectile if it were released under high pressure, the original vessel design was changed after the first test by replacing the lid with a thin, stainless steel rupture disc; a standard 300 psi (2 MPa) stainless pipe flange was welded to the cylinder (pipe). A Type 316 stainless steel safety rupture disc holder and discs with a 300 psi (2 MPa) rating, procured from Fike Metal Products, were used. The rupture disc holder was held in place by bolting a second pipe flange to the first with 12 bolts. Figure 26 shows the configuration of the vessel and closure disc.

The test cylinder assembly was 170 lb (77.3 kg). It is possible that this weight could be reduced by lowering the safety factor and by using aluminum components.

⁵ Rules for Construction of Pressure Vessels, Section VIII, Division 1, Parts UN and UHA (American Society of Mechanical Engineers [ASME], 1974), pp 71-92 and 175-198.

Fabric Form

Because earlier CERL tests had established the strength of Kevlar* fabric, it was selected for use in this study. Fabric strength was important because the fabric bag would be subjected to a significant snap loading when the foam expanded; i.e., one end of the form would be attached to the inside base of the cylinder and the other would be projected horizontally outward from the pressure cylinder. The Kelvar fabric was coated with a polyurethane elastomer to reduce porosity, thus enabling it to contain the foamable mixture both before expulsion from the pressure vessel and during foaming.

Several 1 × 8 in. (25.4 × 203 mm) strips of coated Kelvar fabric were placed in sealable containers with solvents and surfactants to determine the long-term effects of the solvents on the fabric and coating. A group of similar specimens (without solvents or surfactants) were used as controls. During the first week of exposure, specimens from both the control and test groups were removed and tested daily in tension on a Tinius Olson test machine. Subsequently, specimens were removed monthly for testing. The solvent gradually softened the polyurethane coating and made gripping the specimens difficult. The test results showed a slight (less than 20 percent) loss of strength in test vs control specimens. Some of this loss could be attributed to grip slippage and some to grip removal of the cross-weave threads which were less tightly held in the soaked specimens. Although the soak tests continued for 10 months, the change in strength was primarily confined to the first few weeks. Toward the end of the test, the coating was removed from the grip area; the strength of the fabric was very nearly the same as in the unsoaked specimen. Based on these tests, it was believed that the action of the solvents would not substantially affect the performance of the fabric sleeve if it was enclosed in the pressure cylinder with the foamable material.

Each sleeve was made with one double-stitched seam running the length of the tube; Kevlar thread was used for sewing. A circular piece was sewn into one end of the tube; the other was left open (for introducing the foamable material).

Two weights of fabric were used: (1) a lightweight coated Kevlar 29 fabric of 3.5 oz/sq yd (83 gm/m²) that was coated to a total weight of 6.8 oz/sq yd (161 gm/m²), and (2) a heavyweight Kevlar 49 fabric of

5.6 oz/sq yd (132.7 gm/m²) that was coated to a total weight of about 10 oz/sq yd (237 gm/m²).

Test Records for Analysis

A motion picture camera set to run at 2000 frames/second was used to record each test. The foam-filled cylinder was deployed horizontally in front of a white background marked with black vertical lines at 6 in. (0.15 m) intervals (Figure 27). Standard commercial 100-ft (30.5-m) rolls of film (black and white) were used in the movie camera; each roll of film had a running time of about 2.5 seconds. Each test was analyzed using the curve shown in Figure 28. The portion of the curve used in each analysis was established by (1) measuring the length of film from the initiation of camera operation and (2) obtaining the average film speed for that portion of the curve. (The length of the test was short enough so that the film speed error was regarded as minor.)

The test start time was the initial observation of the diaphragm rupture; the test ending time was the full attainment of maximum extension of the foam-filled cylinder. Thus, the number of film frames between the two defined events divided by the frames per second rate gave the deployment time interval.

Deployment Time Tests

Full-scale deployment tests were conducted to establish the minimum practical deployment time. The foamable mixture is listed in Table 4.

The components listed as 1, 2, and 3 were premixed so that the resin beads (component 1) were uniformly coated with a mixture of the surfactant (component 3) which also stuck the microballoons (component 2) to the resin. Premixing was found to be an easy way of ensuring good distribution in the final mixture. The premix was introduced into the fabric sleeve before any solvent was added to it.

The test vessel was prepared in the following steps:

1. The closed end of the fabric sleeve was attached to the inside base of the cylinder by bolting a 4-in. (102-mm)-diameter aluminum plate (inside the sleeve) through the fabric to the vessel end plate. This held the fabric securely to the vessel base.

2. The fabric sleeve was folded in accordin pleats around a paper tube and the assembly was slipped down within the length of the cylinder (Figure 29). The paper tube was then removed (Figure 30). (This

*Dupont registered trademark.

step was usually done before the end plate in Step 1 was installed.)

3. The premix was placed in the folded fabric sleeve and lightly tamped to compact it into the fabric's folds and creases.

4. The open end of the fabric sleeve was folded over and sewn with heavy Kevlar thread, except for a small area at one side.

5. A long outlet tube funnel was placed through the opening in the fabric sleeve so that the end of the tube funnel was near the bottom of the premixed material. A rod was then placed into the tube funnel to prevent it from becoming clogged by resin granules as it was being inserted into the premix. The rod was removed before solvent was added to the funnel.

6. The entire cylinder assembly was placed into an insulated enclosure and surrounded by dry ice to cool it to below the boiling point of the solvent (methyl chloride).

7. Components 4 and 5 (see Table 4) were poured into the funnel cone and allowed to gravity-flow into the premix.

8. The funnel was removed immediately after the solvents were placed in the premix and the remaining section of the sleeve was sewn together. The end was then folded down below the flange face.

9. The rupture disc holder (with disc installed) was placed in position on the fixed flange (Figure 31). The free flange was placed on the other side of the rupture disc holder (Figure 32) and 12 attachment bolts placed in position through the two flanges (Figure 33). The bolts were then tightened with a torque wrench to the recommended force level. (The amount of torque load used to pretension the bolts depended on the strength of the rupture disc; it was usually 120 in.-lb [13.56 N-m] for the highest pressure disc; this amount of torque was used for all tests.)

10. The pressure vessel assembly was removed from the dry ice and allowed to warm to room temperature. After this warmup period, the vessel seal was checked by submerging it in water. Because there was no gasket to hold the seal between the disc holder and the fixed flange, a 4-mil (0.1-mm)-thick polyethylene film ring the size of the disc holder was placed between the holder and the fixed flange.

11. The pressure vessel was placed in a circulating air oven at 120°F (49°C) for 24 hours to speed up the dissolving process.

12. Just before testing, the pressure vessel was transferred to a cradle mounted on a block of concrete (about 3500 lb [1590 kg]; Figure 34) and secured by two steel bands. The vessel's internal pressure was then adjusted with nitrogen from a cylinder to within the rupture pressure range of the diaphragm. During the transfer of the heated, pressurized vessel (and during the test) a videotape was made of all activities (to be used as a record in case of an accident).

Discussion of Tests

The initial full-scale tests demonstrated some of the difficulties inherent in conducting and recording relatively rapid events. As previously stated, the total running time of the motion picture camera was about 2.5 seconds; therefore, it was desirable to have the event being filmed coincide with the midpoint (or later) of the film's running time, so that the film speed would be at least somewhat normalized. The original intent was to rupture the diaphragm (disc) by a rapid pulse application of gas pressure into the foamable contents. It was anticipated that a pressure about 50 percent more than the rated rupture pressure would cause instantaneous failure of the diaphragm, thereby releasing the contents. The first test used this technique; gas pressure was supplied from a nitrogen pressure cylinder and a small volume ballast cylinder. The camera was started and a full-opening ball valve between the ballast tank and the test vessel was opened; however, the diaphragm did not rupture until after the film had run through the camera because the time required to stretch the disc had not been considered. It was decided that the degree of uncertainty about the actual time of failure was too unreliable to allow this technique to be useful in this particular test situation. A highly precise method of rupturing the disc would have been to use explosive-actuated rupture discs; however, they were not used because of CERL safety requirements. A compromise method was devised. After the test vessel had been pressurized to about 10 percent below the nominal disc rupture pressure (as established in quality control tests by the manufacturer), an air rifle projectile was fired into the disc to initiate failure. Disc failure was then propagated by the pressure within the vessel. Trial tests at CERL established that the internal pressure had to be near the disc failure pressure before the entire disc would fail; otherwise only simple venting would occur.

This technique was used successfully throughout the remainder of the test series. The projectile was fired from behind a safety shield that was in view of, but out of alignment with, the rupture disc of the pedestal-mounted test device. The air rifle operator also actuated the camera. This allowed the operator to effectively regulate both the event timing and the photography. Regular speed movies were also made to record the real time of each test.

The early tests using the air-projectile method revealed another problem area. The fabric sleeves, although constructed of high-strength fabric and thread, failed. Failure occurred where the open end of the sleeve had been folded over and hand sewn. But when this problem was corrected, the longitudinal seam failed. Correction of the longitudinal seam failure resulted in the sleeve and contents disengaging from the anchor point within the cylinder. The mode of failure was the same in three cases; i.e., the threads separated within the fabric and pulled out of the edge of the fabric near the seam line. (The fabric did not fail in a region away from the edge in any test.) A new group of sleeves were made with seams reinforced by sewing, folding over, and sewing again. Figure 35 shows the original seam and Figure 36 shows the sewing modifications used to make the seam more secure. The end cap circle was reinforced by sewing two 4 X 24 in. (101 mm X 0.61 m) strips crossed over the end piece. These strips were then sewn to the sides of the sleeve (Figure 37). This arrangement allowed more fabric at the end and prevented the edges from pulling out of the circular end cap.

Three different pressure-rated rupture discs were used. The early tests used 300 psi (2.07 MPa) discs. However, this high initial pressure made it difficult to hold the system together during deployment. Subsequently, two lower rated discs were used; one had a 150 psi (1.03 MPa) rating and the other had a 200 psi (1.38 MPa) rating. The lower pressure discs provided reliability with a less vigorous discharge.

The foam material made by the system was fully expanded and firm immediately after the deployment process was completed. Figure 38 shows a fully extended cylinder resulting from one of the deployment time tests.

Test Results

Ten tests were conducted. The results of each test are described below, and a summary table follows the discussion (Table 5).

Test 1. The first test was not recorded. The mode of operation was to cause discharge by overpressuring the diaphragm.

Test 2. The sewing on the projected end of the fabric sleeve failed, and the foam did not stay in the bag. No time record was made of the test.

Test 3. The foam partially expanded. The solvent apparently leaked out during the heating cycle and the end of the bag ripped out, allowing a partially foamed, very dense slug to shoot across the test room.

Test 4. Similar to Test 3, except the foam material was not ejected from the pressure cylinder. (All tests following Test 4 were leak-tested to prevent solvent loss.)

Test 5. The side seam of the bag (near the projected end) ripped open as the deployment occurred. A time record was made even though the assembly did not hold together.

Test 6. The disc failed to rupture when anticipated; results were similar to Test 5, except no record was made.

Test 7. A 200 psi (1.38 MPa) disc was perforated with an internal pressure of 175 psi (1.21 MPa). A time record was made. The bag failed from the anchor point within the pressure cylinder.

Test 8. A 150 psi (1.03 MPa) disc (the lowest pressure-rated disc) was used; the pressure vessel functioned inadvertently, and there was no record made of the test. The fabric sleeve held together and stayed attached within the cylinder.

Test 9. Test 9 also used a 150 psi (1.03 MPa) disc; the internal pressure at the time of test was 120 psi (0.82 MPa). The assembly held together; a time record was made.

Test 10. Test 10 used a 200 psi (1.38 MPa) disc; the internal pressure at the start of the test was adjusted to 175 psi (1.21 MPa). The sleeve had a modified seam along its length and reinforcing strips at the fixed end, i.e., the end in the pressure cylinder. The assembly held together; a time record was made.

Since it was not within the scope of this study to establish all operational parameters, only enough tests were run to obtain a very short deployment time. No

efforts were made to ease the ejection friction by lubricating the inside of the cylinder. Although data on ejection or deployment time are not consistent with what might be expected (i.e., shorter operating time at higher pressure), other factors such as fabric sleeve to pressure vessel side-wall friction may have influenced performance. A higher internal pressure probably increased the initial friction between the fabric sleeve and vessel wall and retarded ejection.

Statistically valid data were not sought; only enough tests were conducted to give a reasonably reliable idea of the practical minimum deployment time.

5 CONCLUSIONS

1. A single-component foam-generating system for deploying a 0.5×10 ft (0.15×3.05 m) foam-filled fabric cylinder is practical. A two-component reactive foam system is also practical, but requires a longer operating time.

2. A full-end-opening tubular pressure vessel can be used as a container for a foam-generating system.

3. High-strength coated fabrics (which are resistant to solvent effects) are satisfactory for the sleeve used to contain the foamed material. This fabric tube can be packaged within the pressure vessel with the foamable mixture contained inside it. Special sewing is

required to withstand the loads imposed by the force of deployment.

4. Deployment times of approximately 50 milliseconds are attainable with a relatively easy-to-control system.

6 RECOMMENDATIONS

Based on the results of this study, the following recommendations are made:

1. If a specific time requirement is anticipated for a particular use, additional tests should be performed to establish the statistical reliability of the deployment time achieved in this study.

2. Thrust and reaction forces involved in the ejection process should be measured.

3. Pressure vessel designs that weigh less than the test system used in this study should be considered.

4. A method of premixing and dissolving bulk amounts of the foamable mixture should be developed so it can be transferred quickly and easily to the pressure vessel.

5. The range of sizes and shapes of foam-filled shapes attainable with a single-component foam-generating system should be investigated.

Table 1
Polystyrene Foam Formulation
(Constituent, Description, and Parts by Weight)

Constituent	Description	Parts by Weight
Resin:	High molecular weight polystyrene LUSTREX HH-101*	0.6376
Nucleating Agent:	Microballoons IG 101*	0.0101
Lubricant/Surfactant:	Triton X-200*	0.0243
Pneumatogen:	Methyl chloride	0.2794
Auxiliary Blowing Agent:	Trichloromonofluoromethane (R-11)	0.0486

*Materials suppliers are listed in Appendix.

Table 2
Foam Formulation and Quantities

A.	Resin	130.3 grams
	Nucleating agent	2.1 grams
	Lubricant	4.9 grams
B.	Dichloromonofluoromethane (R-11)	9.9 grams
	Methyl chloride	57.1 grams

Table 3
Small Foam Unit Test Results*

Temp. of Unit °F (°C)	Temp of Water °F (°C)	Foam Density lb/cu ft (g/m ³)	Length in. (mm)	Diameter in. (mm)	Remarks
-65 (54)	27.5 (-2.5)	--	--	--	No foaming action
-10 (-23)	27.5 (-2.5)	--	--	--	Slight expansion of foam (Figure 18)
27.5 (-2.5)	27.5 (-2.5)	2.6 (41.6)	155 (3.9)	1.12 (28)	Very slow foam generation (3-5 sec) (Figure 19)
67 (19)	67 (19)	2.4 (38.4)	152 (3.9)	1.38 (35)	Moderate foam generation (1-2 sec) (Figure 20)
107 (42)	107 (42)	1.6 (25.6)	163 (4.1)	1.75 (44)	Rapid expansion of foam (-1 sec) (Figure 21)
160 (71)	160 (71)	0.98 (15.7)	158 (4.0)	2.5 (63.5)	Very rapid expansion of foam (<0.5 sec) (Figure 22)

*One unit was tested at each of the indicated conditions.

Table 4
Full-Scale Test Formulation

Component	Amount
1. HH-101 PS resin	5.00 lb (2.27 kg)
2. IG 101 microballoons	0.08 lb (36 g)
3. Triton X-200 surfactant	0.20 lb (90.8 g)
4. Methyl chloride (solvent)	2.20 lb (1 kg)
5. Dichlorodifluoromethane (R-12)	0.38 lb (172.5 g)

Table 5
Test Results (Deployment Time)

Internal Pressure Test No.	Film Speed psi (MPa)	Film Frames/Sec	Deployment Total Frames	Time (milliseconds)
5	275 (2.07)	2300	110	47.8
7	175 (1.21)	1080	43	39.8
9	120 (0.83)	1900	104	55.0
10	175 (1.21)	1750	90	51.4

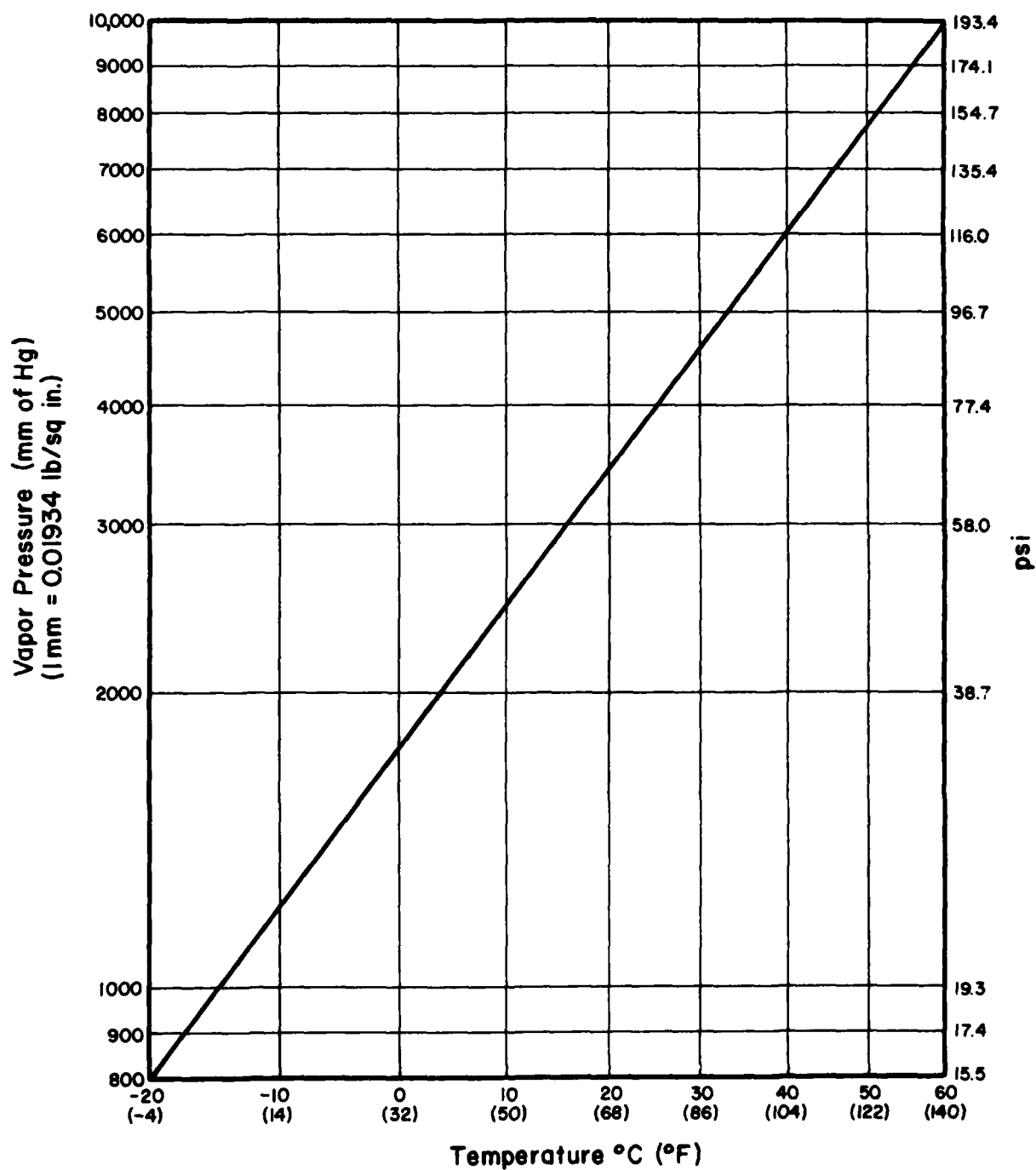


Figure 1. Vapor pressure curves of methyl chloride.

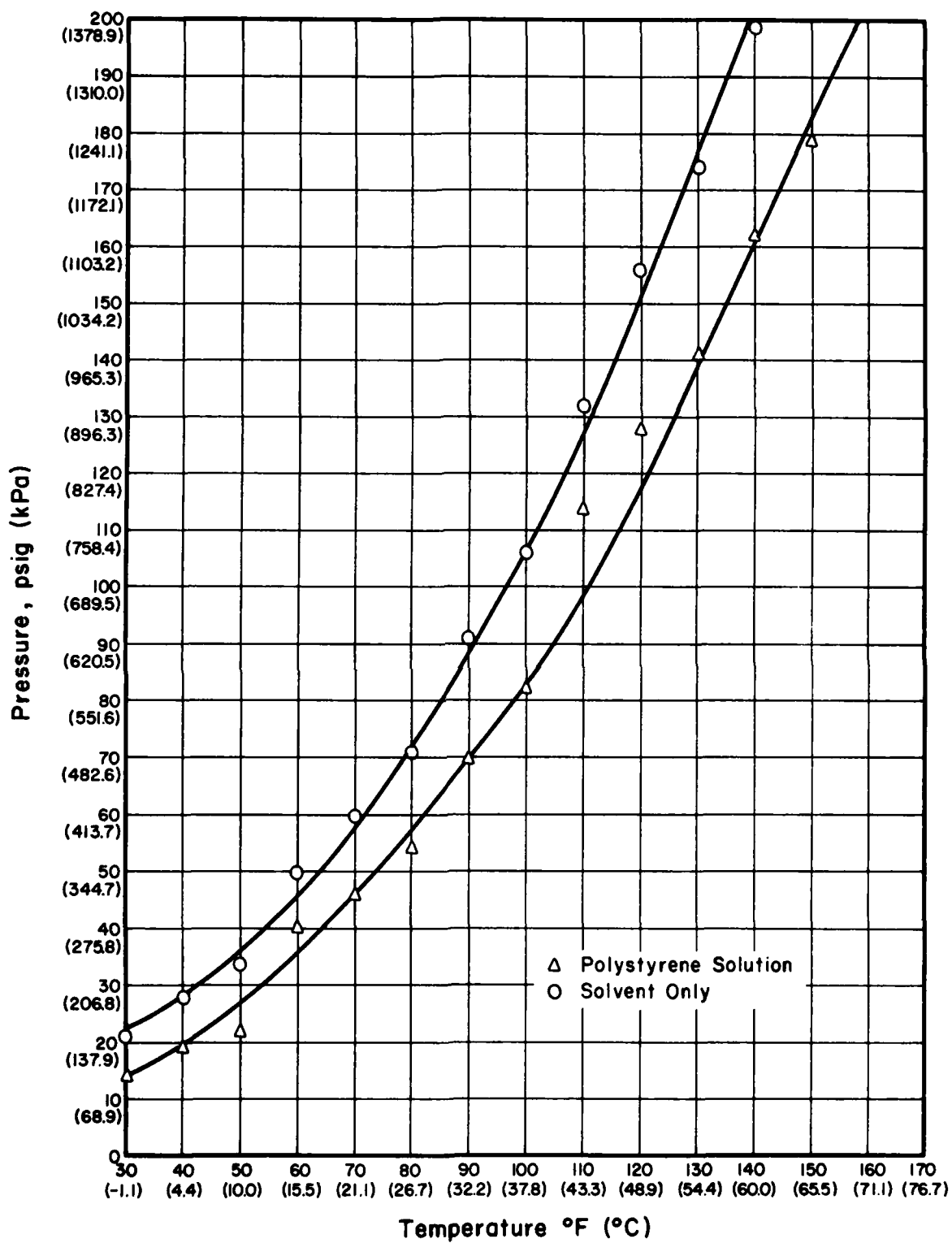


Figure 2. Comparison of vapor pressure curves of methyl chloride and methyl chloride-polystyrene solution.

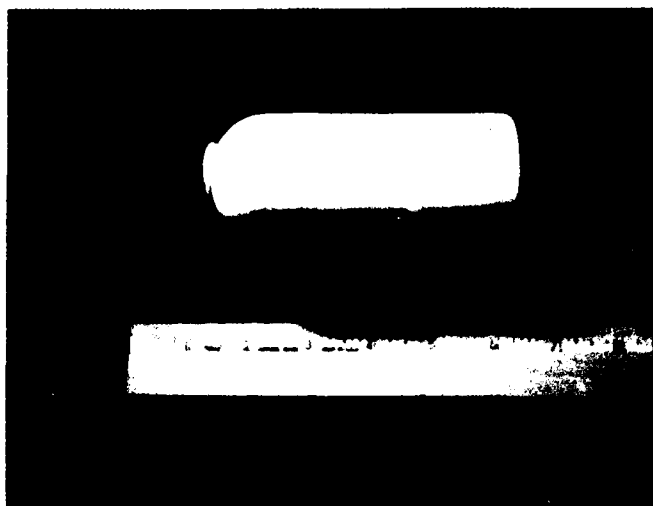


Figure 3. Side view of aerosol can.

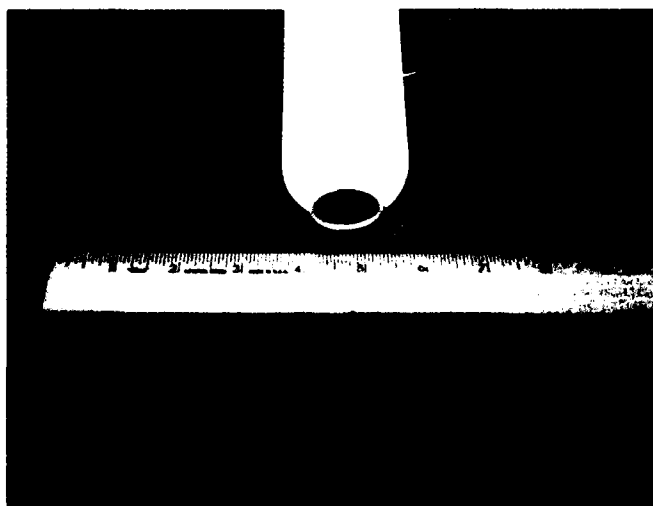


Figure 4. End view of aerosol can showing rolled edge and crimping shoulder in opening.

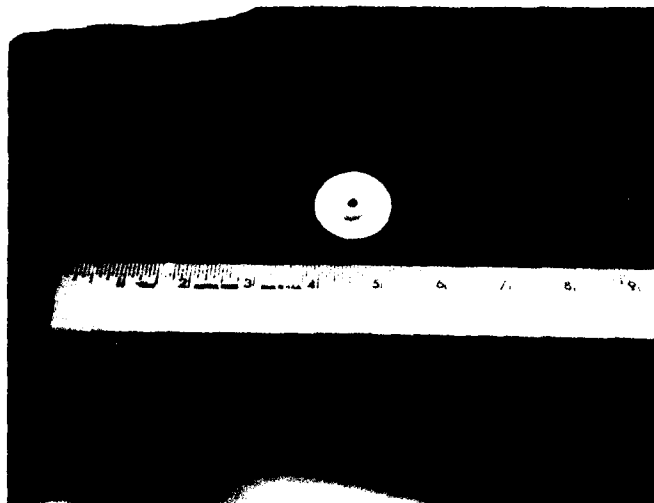


Figure 5. Closure cup.

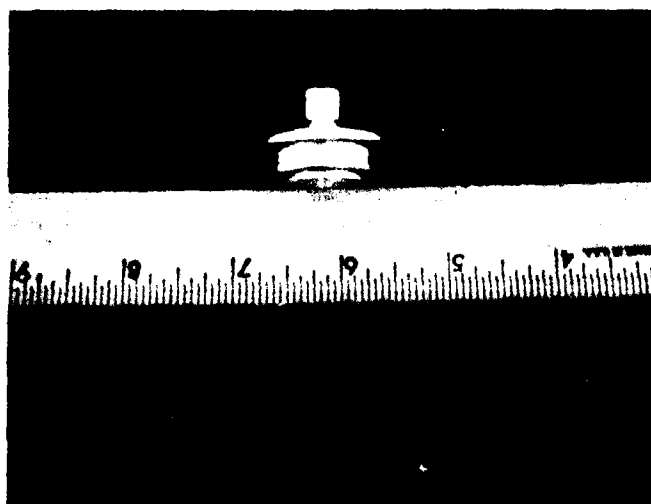


Figure 6. Side view of cup modification with enlarged orifice.

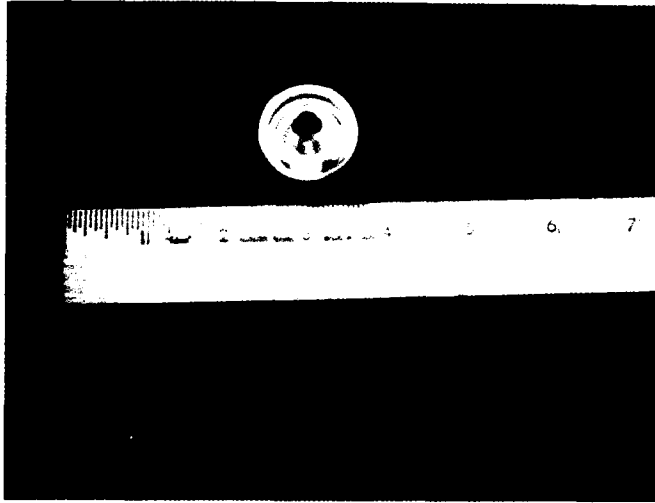


Figure 7. Throat view of orifice and closure cup.

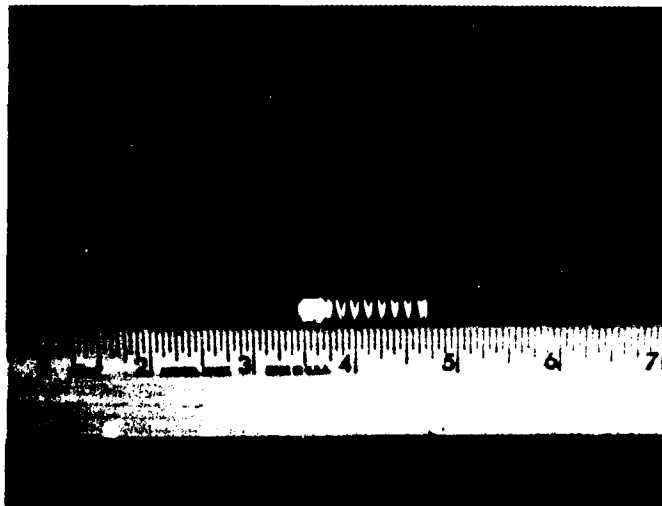


Figure 8. Spring and plunger assembly used to seal against O-ring.



Figure 9. Spring and plunger assembly in place in orifice throat.



Figure 10. Spring cap and retainer clip in place.

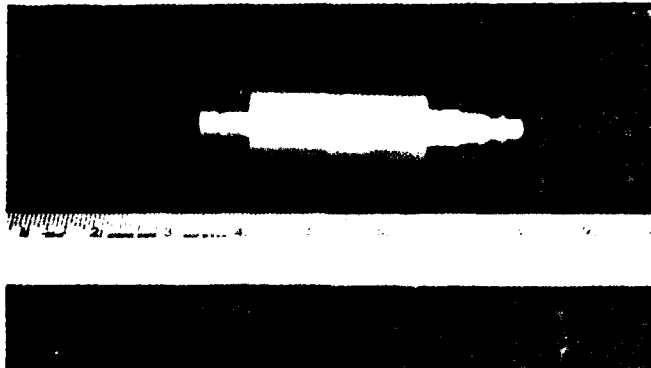


Figure 11. Orifice seal test device.

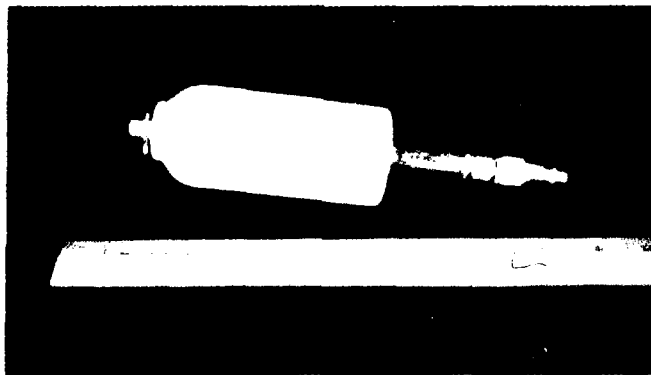


Figure 12. Closure cup, can, and release mechanism seal test device.

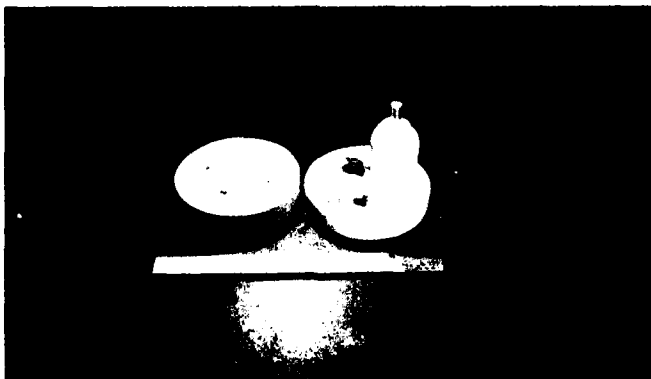


Figure 13. Wooden adaptors for mixer.

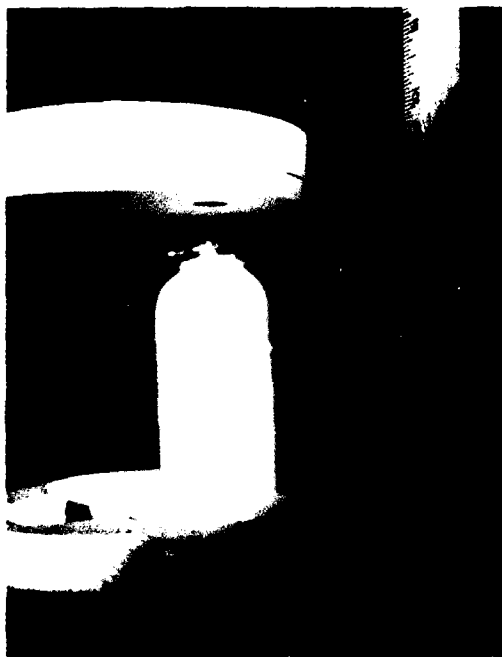


Figure 14. Foam unit in adaptor (bottom and top).

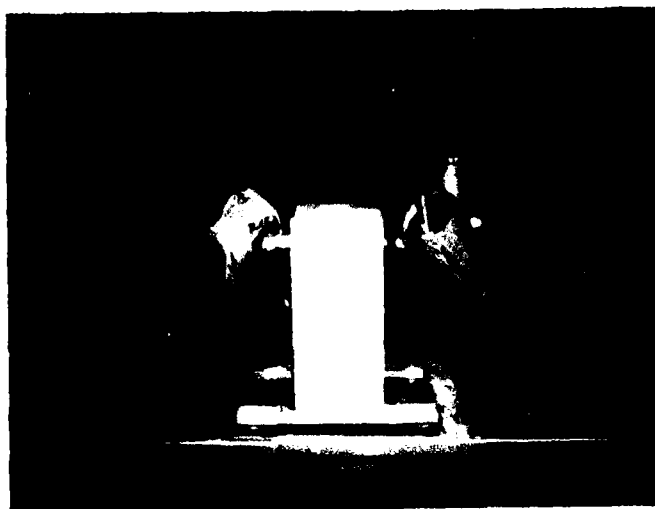


Figure 15. End-over-end mixer (20 rpm).



Figure 16. Foam extruded through small orifice.

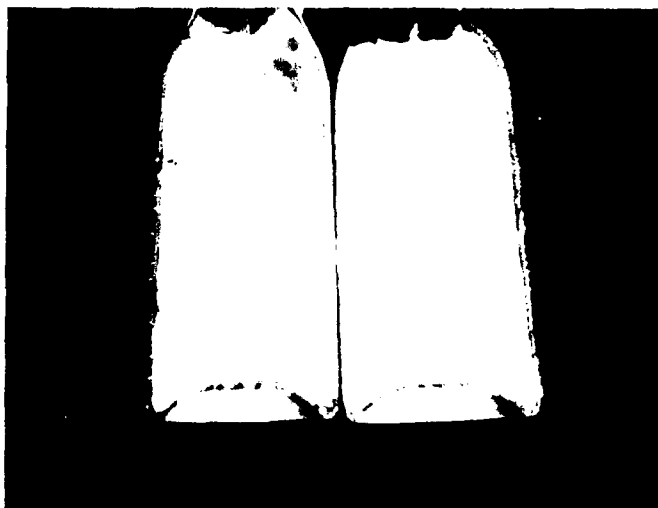


Figure 17. Post-functioning cutaway view of can with remaining foam.

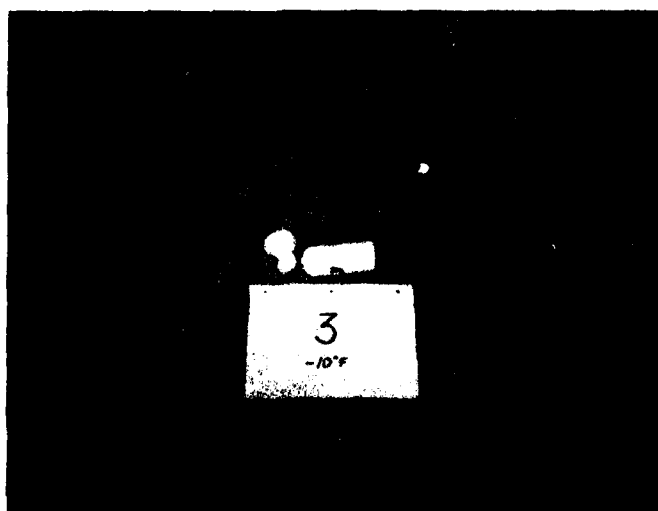


Figure 18. Foam expansion at a water temperature of 27.5°F (-2.5°C).

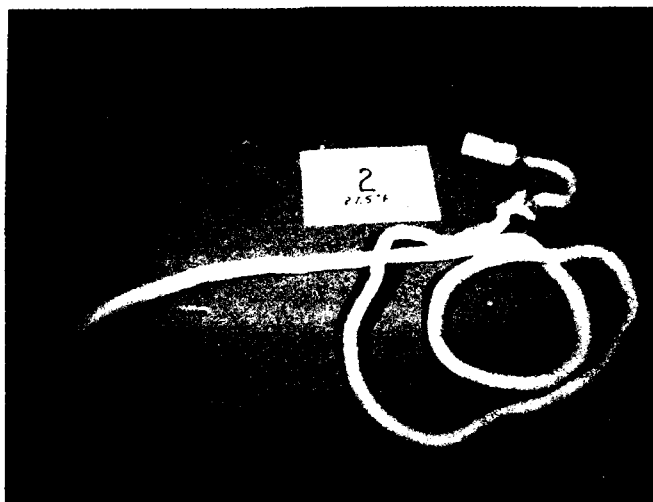


Figure 19. Slow foam generation (3 to 5 seconds) at a water temperature of 27.5°F (-2.5°C).

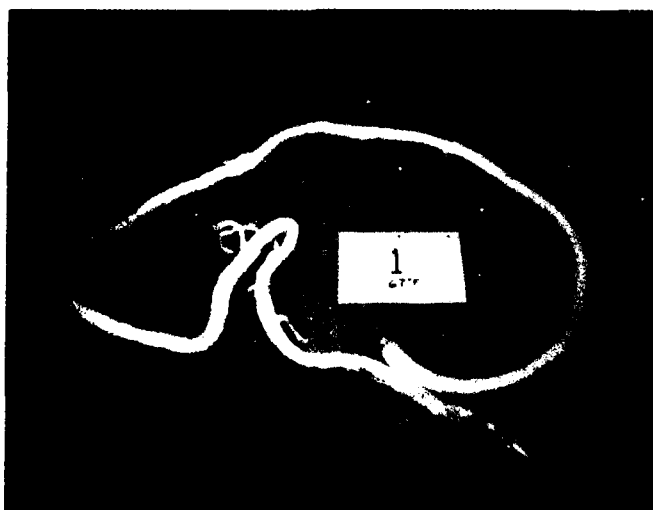


Figure 20. Moderate foam generation (1 to 2 seconds) at a water temperature of 67°.



Figure 21. Rapid foam expansion (about 1 second) at a water temperature of 107°F (42°C).



Figure 22. Very rapid foam expansion (less than 0.5 second) at a water temperature of 160°F (71°C).



Figure 23. Foam generated into a lightweight nylon fabric sleeve.

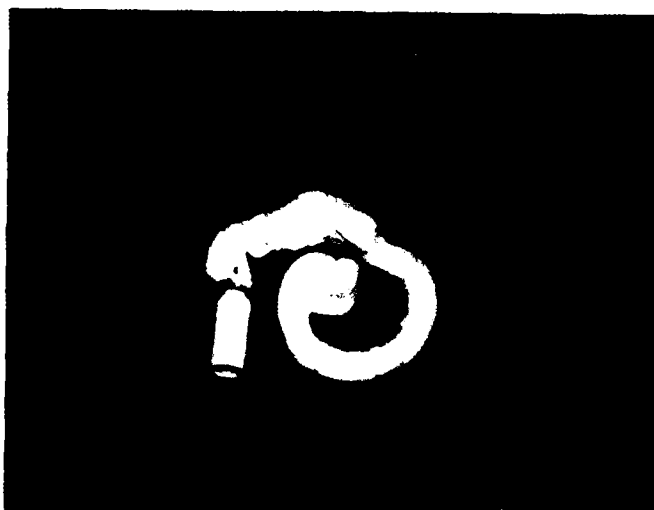


Figure 24. Can and foam from Figure 23.



Figure 25. Foam generated into straight sleeve of polyethylene film.

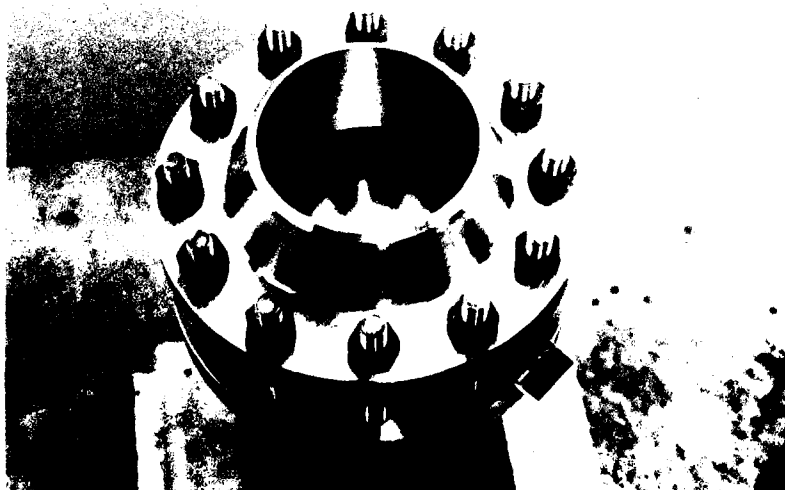


Figure 26. Rupture disc in place.

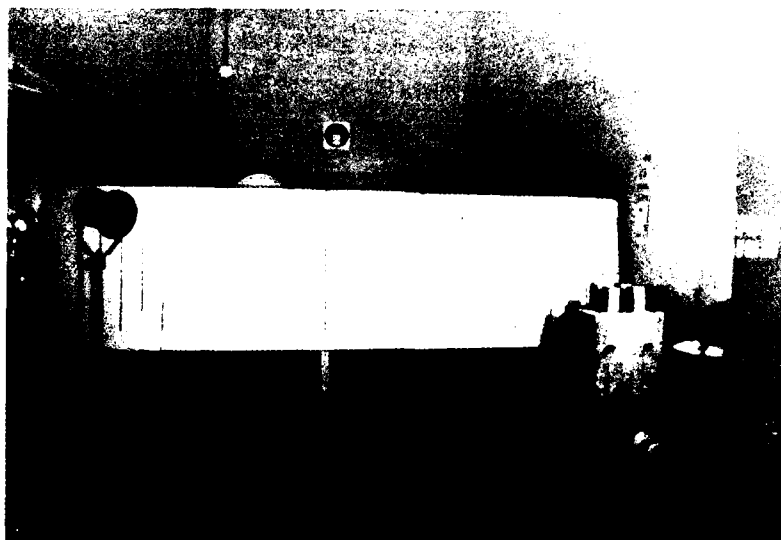


Figure 27. Background screen.

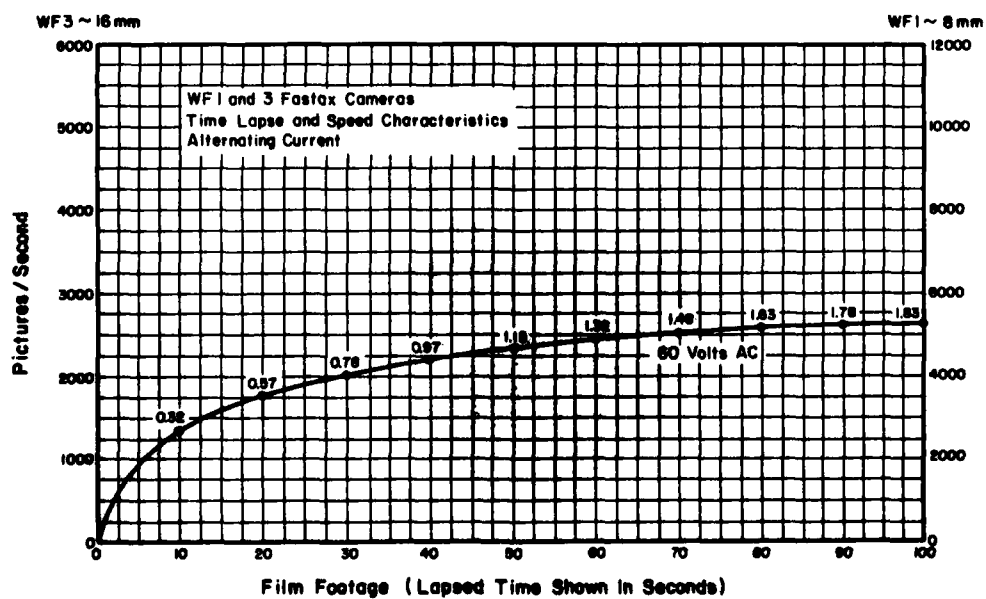


Figure 28. Film speed curve.

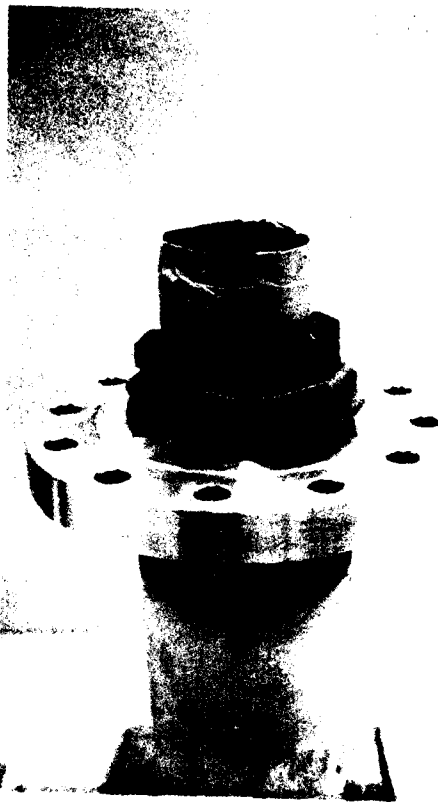


Figure 29. Paper tube (guide for sleeve installation).

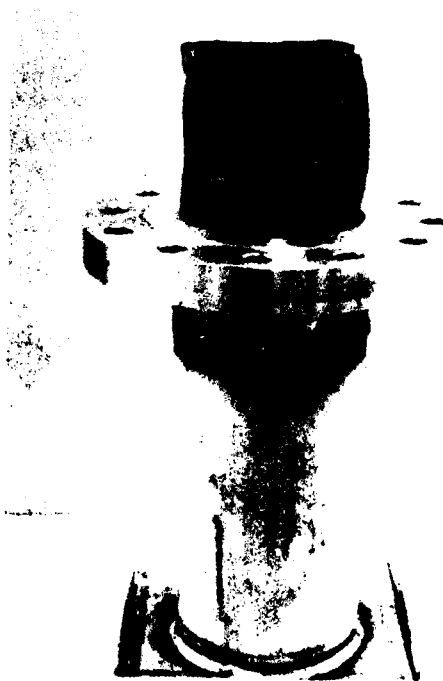


Figure 30. Fabric sleeve in vessel.



Figure 31. Rupture disc and holder.

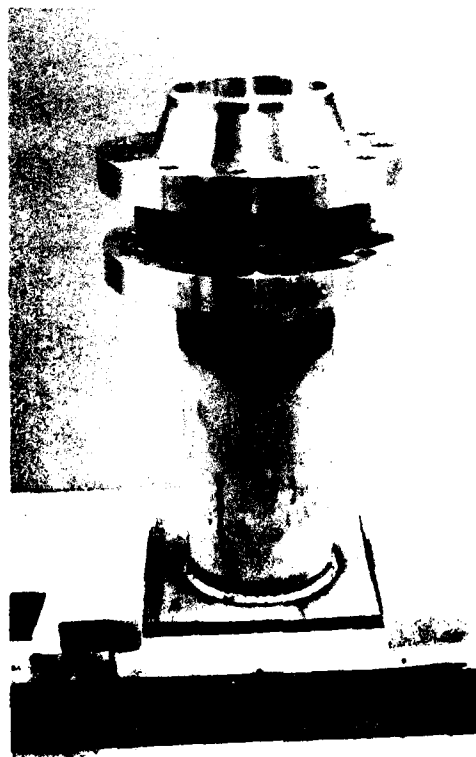


Figure 32. Free flange installation.

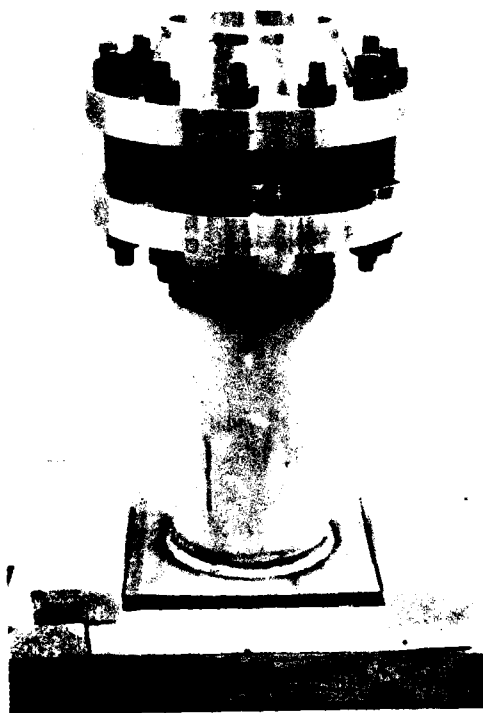


Figure 33. Completed assembly.

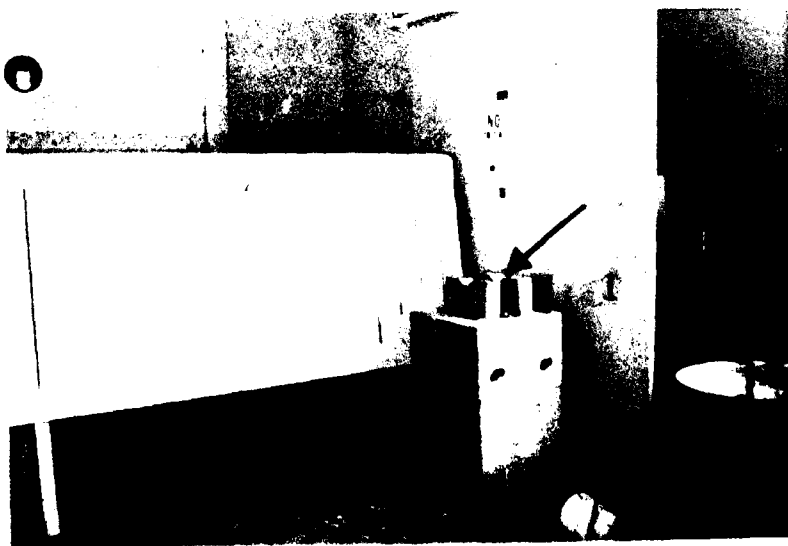


Figure 34. Test facility (arrow shows cradle mounted on a concrete pedestal).

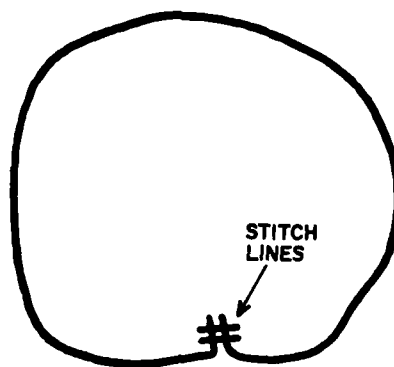


Figure 35. Original longitudinal seam (sewn then turned inside out).

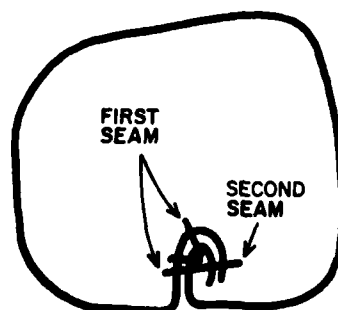


Figure 36. Modified seam (sewn then turned inside out).



Figure 37. Deployed foam-filled cylinder.



Figure 38. Fully extended cylinder.

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**APPENDIX:
MATERIAL MANUFACTURERS/SUPPLIERS**

The materials used in this study were manufactured or supplied by the companies listed below. Equivalent materials are generally available from other suppliers.

Polystyrene resin: Lustrex HH-101
Monsanto Research Corp.
Addyston, OH 45001

Glass microballoons: IG-101
Emerson and Cuming, Inc.
Dielectric Materials Division
869 Washington St.
Canton, MA 02201

Surfactants: Triton X-200
Rohm and Haas Company
Independence Mall West
Philadelphia, PA 19105,

Igepal Co-970
GAF Corp.
140 W. 51st St.
New York, NY 10020

Methyl chloride:
Matheson Gas Products
275 Valley Brook Avenue
Lyndhurst, NJ 07071

**Trichloromonofluoromethane (Freone 11),
Dichlorodifluoromethane (Freon 12), and
Bromotrifluoromethane (Freon 13B1):**
E. I. du Pont de Nemours & Co., Inc.
Du Pont Building
Wilmington, DE 19898

Aerosol cans:
Peerless Tube Co.
66 Locust Ave.
Bloomfield, NJ 07003

Closure cups:
Precision Valve Co.
700 Nepperhan Ave.
P.O. Box 309
Yonkers, NY 10702

Rupture discs:
Fike Metal Products
Blue Springs, MO 64015
Bolted Type Fike Rupture Unit Assemblies.
Assembly G, Free Outlet, insert type

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